Assessment of Piezoelectric Materials for Energy Harvesting in Roadways

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About the information in this report

- Information was derived from what was available from vendors and manufacturers, including scientific literature, marketing materials, press releases, and physical calculations
- Two methods were used to determine the levelized cost of electricity (LCOE in $/kWh) and capital costs ($/kW): The first method relied upon vendor data to independently estimate these parameters. The second method used traffic data specific to the US to separate out traffic effects on the energy harvesting system and cross-check the results against vendor claims.
- The LCOE and capital cost claims by vendors fall within the estimates made by DNV. However, the DNV assessment identified uncertainties that contribute to a broad spread in the energy and capital costs.
- The findings also illustrate the need to verify maximum power output on a per module level in order to ease the assessment process. In the same way that wind turbines and solar panels have a nameplate power rating, the same is needed for piezoelectric technologies in order to isolate performance from location specific factors.
- Areas of potential mutual exclusivity were found, such as agreement between LCOE and CAPEX, for example.
- None of this information is intended to favor one manufacturer over another. Given the information available, these assessments are an objective review of what appears to be possible given the engineering and scientific tools available.

Outline

- Background information
- Method for evaluation
- Types of piezoelectric energy harvesting technologies
- Installation method
- Effect of traffic – vehicle types and volume
- Cost metrics
- Estimates of LCOE based on vendor claims
- Estimates of LCOE based on traffic approach
- Parameters with possible mutual exclusivity
- LCOE and capital cost ranges
- Ways pathways to test

General Data

Walking

Consumer electronics

Limit of human hearing

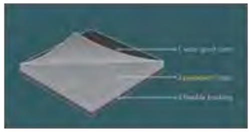
Piezoelectric sensors

Ultrasonography

Vibration Energy Harvesting

Low Frequency				High Frequency
1 Hz	60 Hz	20,000 Hz	100,000 Hz	1,000,000 Hz

Piezoelectric Floor



Solar Panel

Power Plant

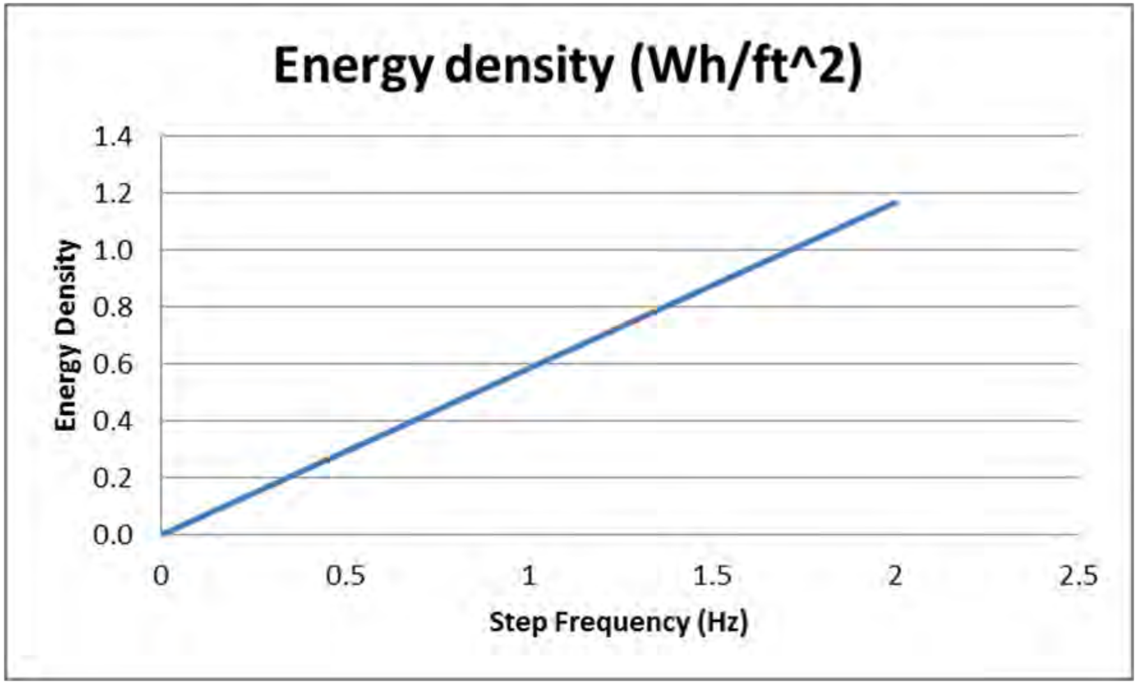
Vibration

Low Power → High Power

1 W	200 W	200,000,000 W
1 Wh	200 Wh	200,000,000 Wh

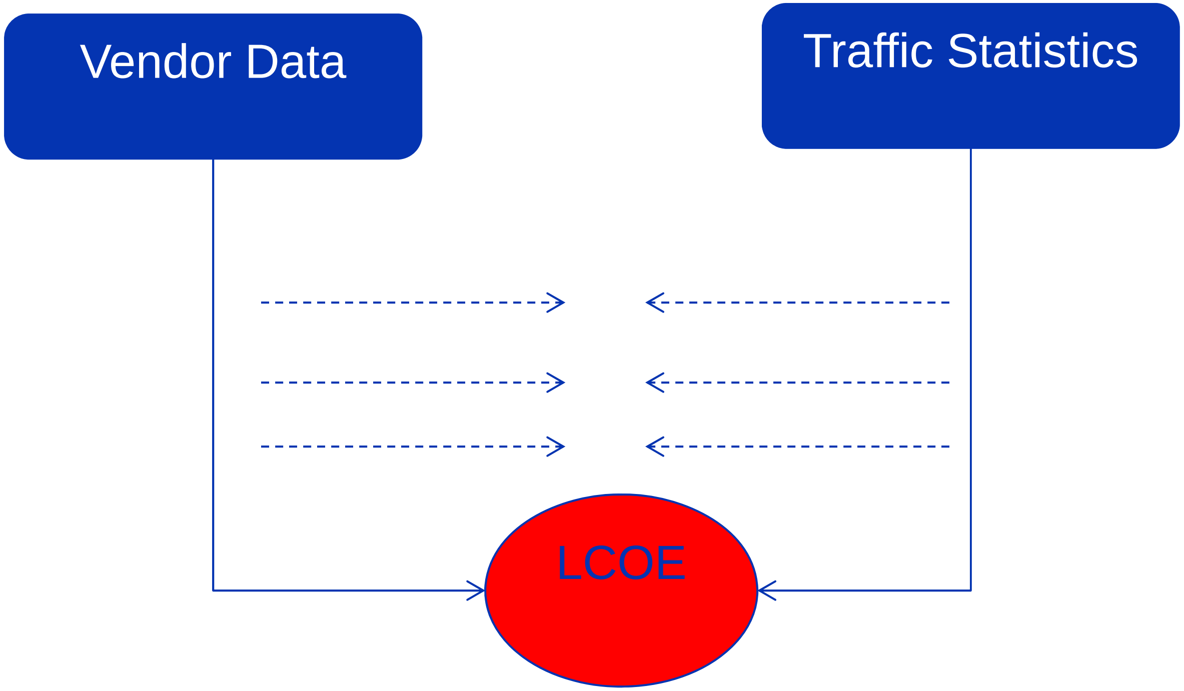
Low Energy → High Energy

EXAMPLE: Energy density for foot-traffic energy harvesting systems



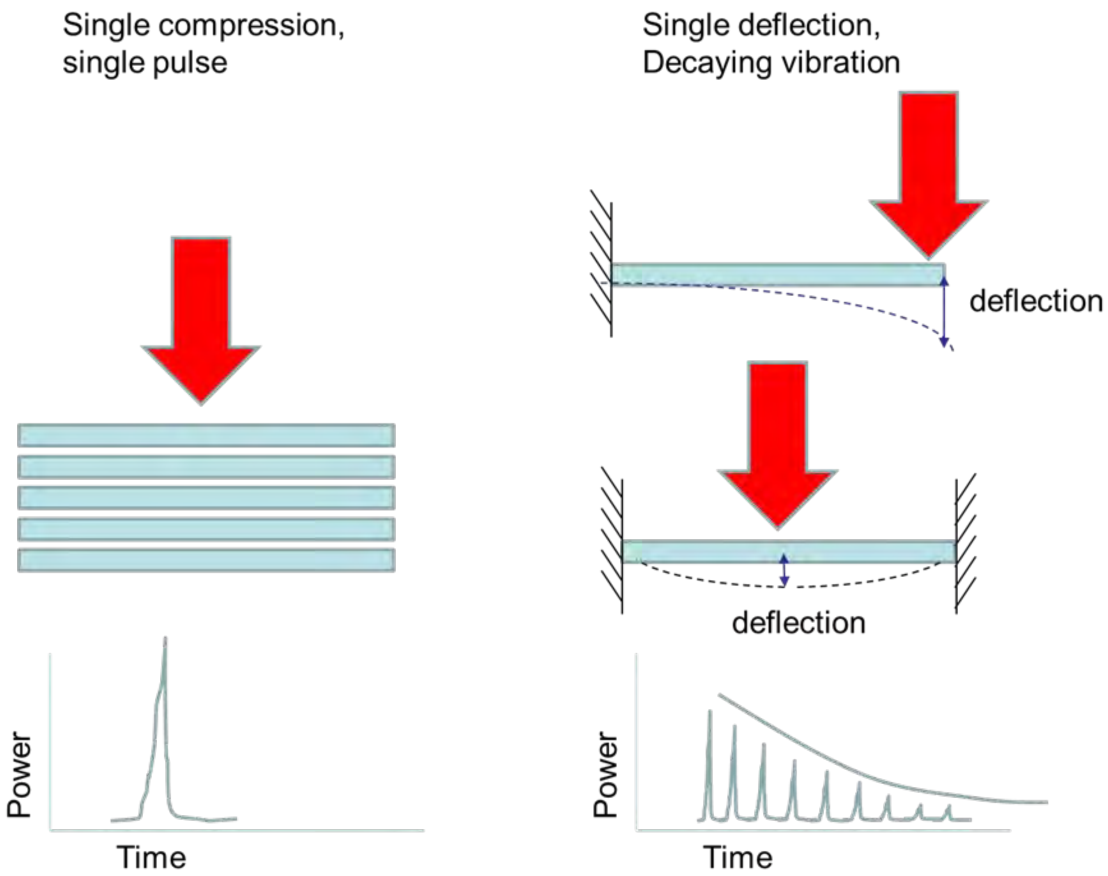
More traffic = more power = more energy

Cross-Check of Evaluation Method



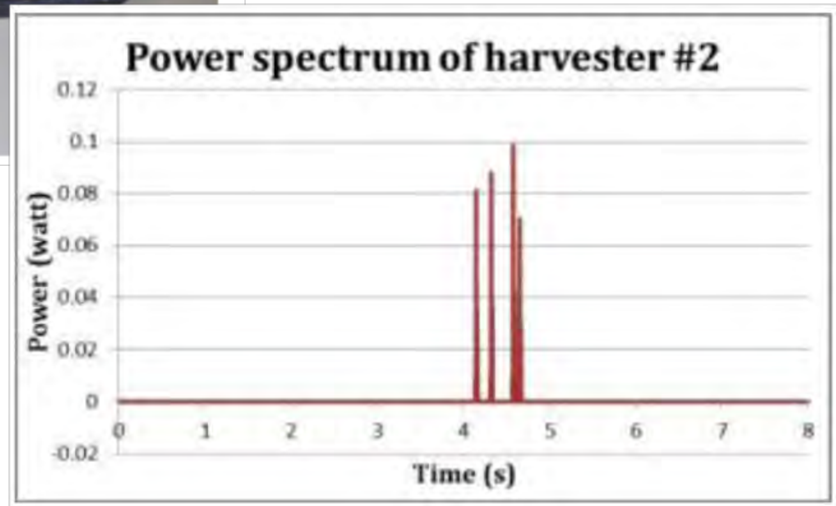
Determination of LCOE with two different methods while cross-checking assumptions

Two ways to harvest energy

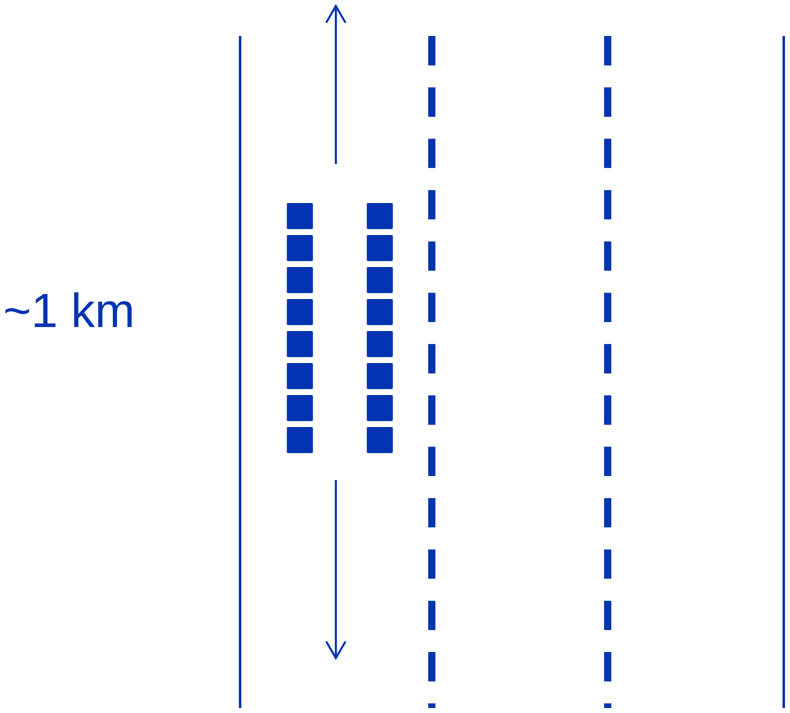


A simplified piezoelectric energy harvesting device

Source: Virginia Tech



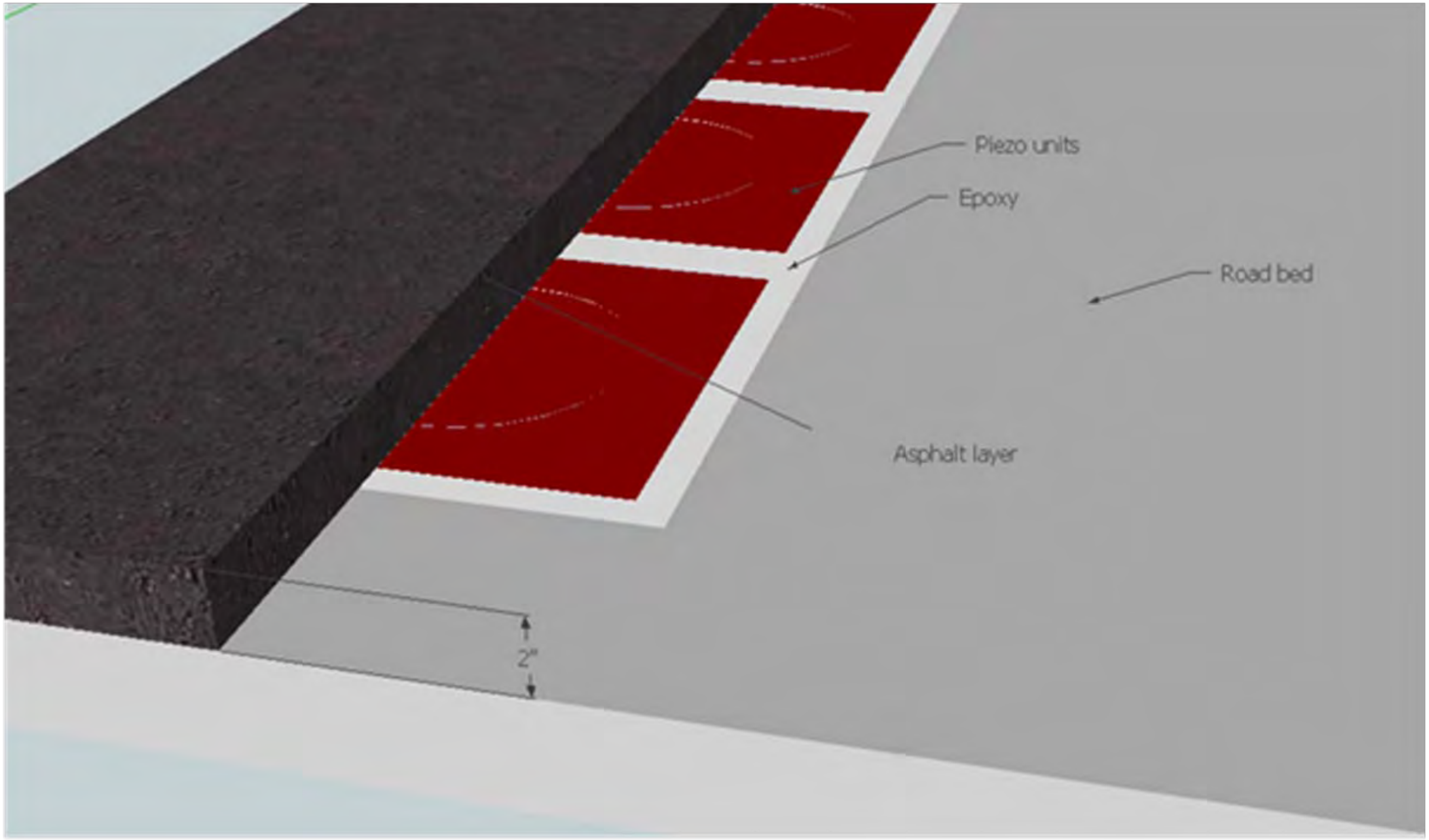
General Energy Harvesting System Layout



Considerations:

- Embedding systems in concrete
- Matching track width of vehicles
- Maintaining lanes

Roadway installation



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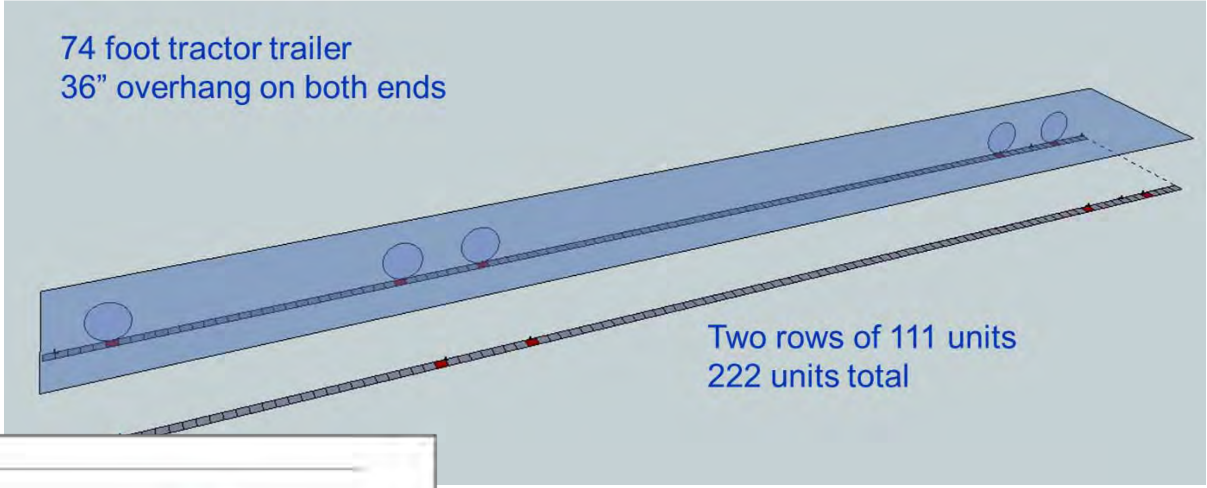
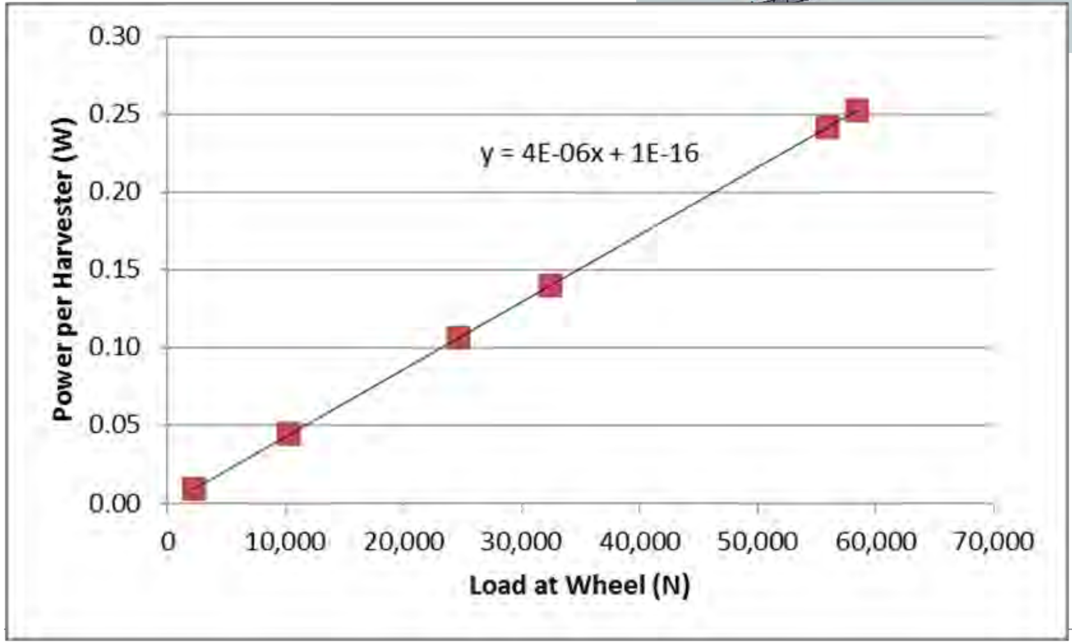
Effect of vehicle characteristics on capacity factor





Demonstrated power output is higher than what Berkeley calculated is possible. Commercial designs are likely higher still.

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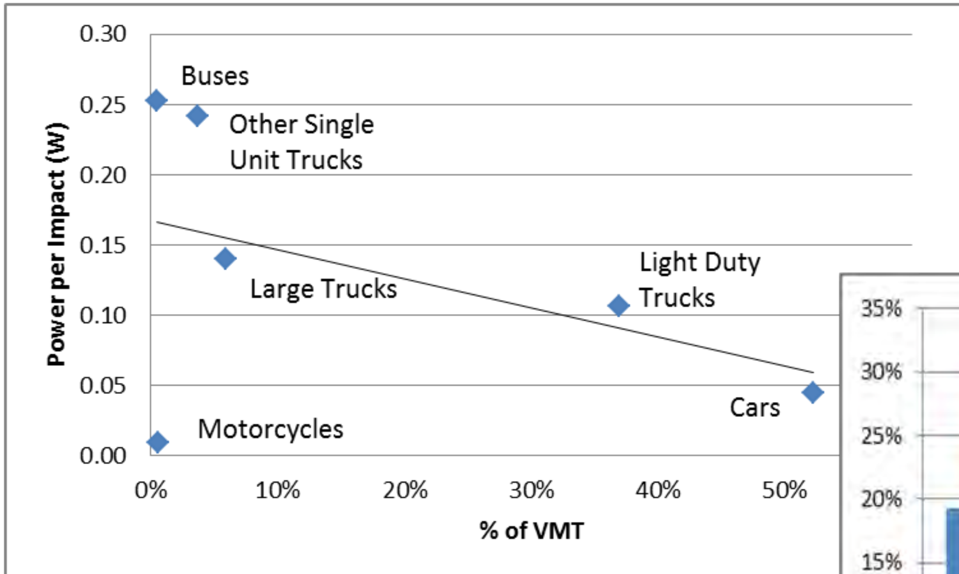
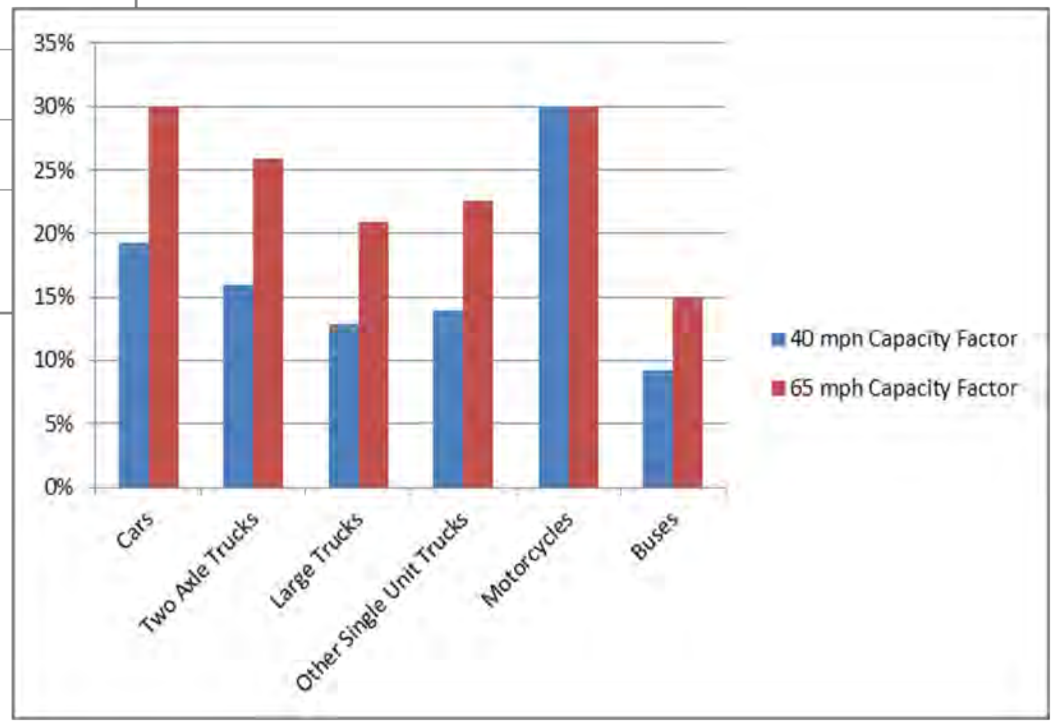
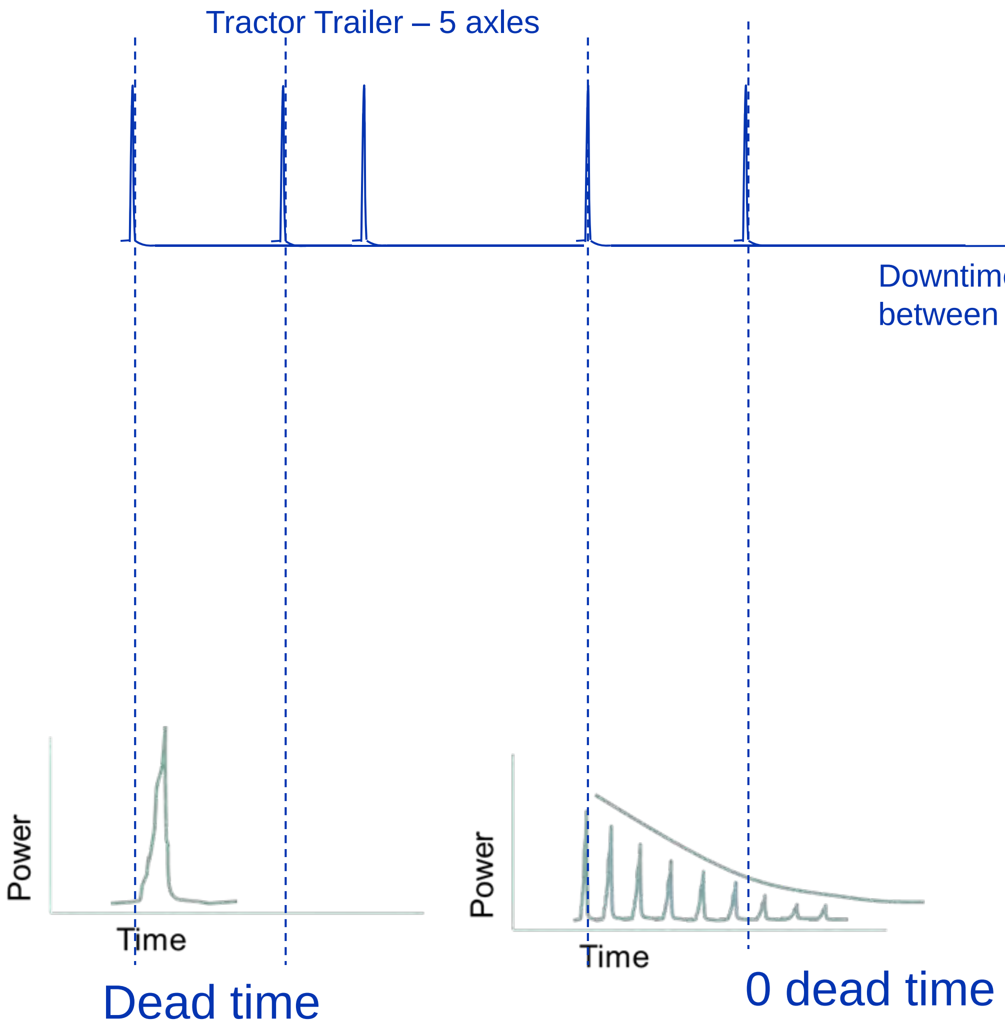
Traffic Challenges





Increasing the Length of Power Pulse increases Capacity Factor



Net effect: capacity factor is a function of spacing between vehicles, pulse duration, vehicle speed, and wheelbase

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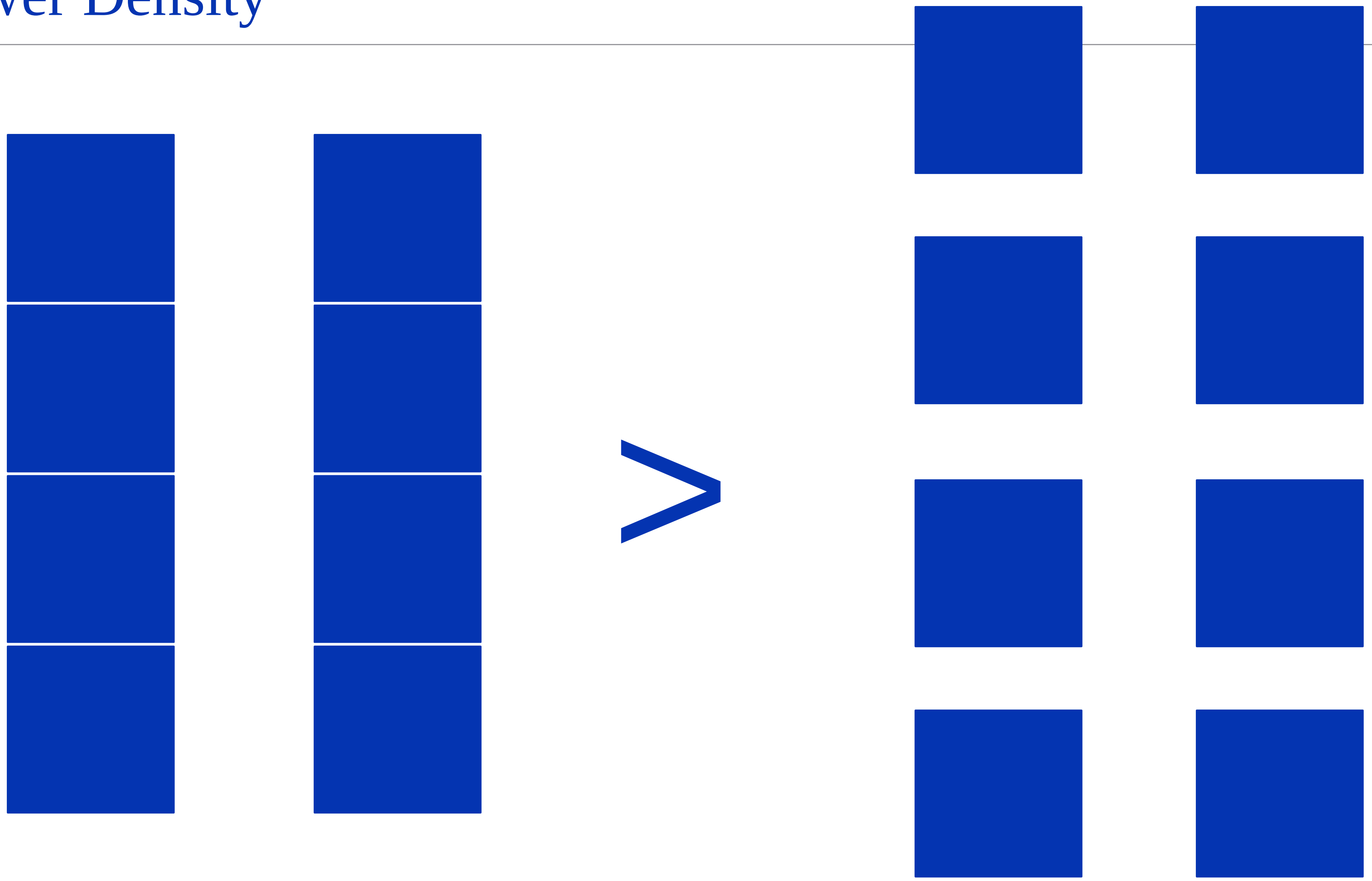
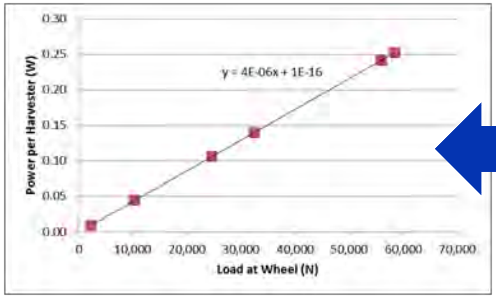
Power Density



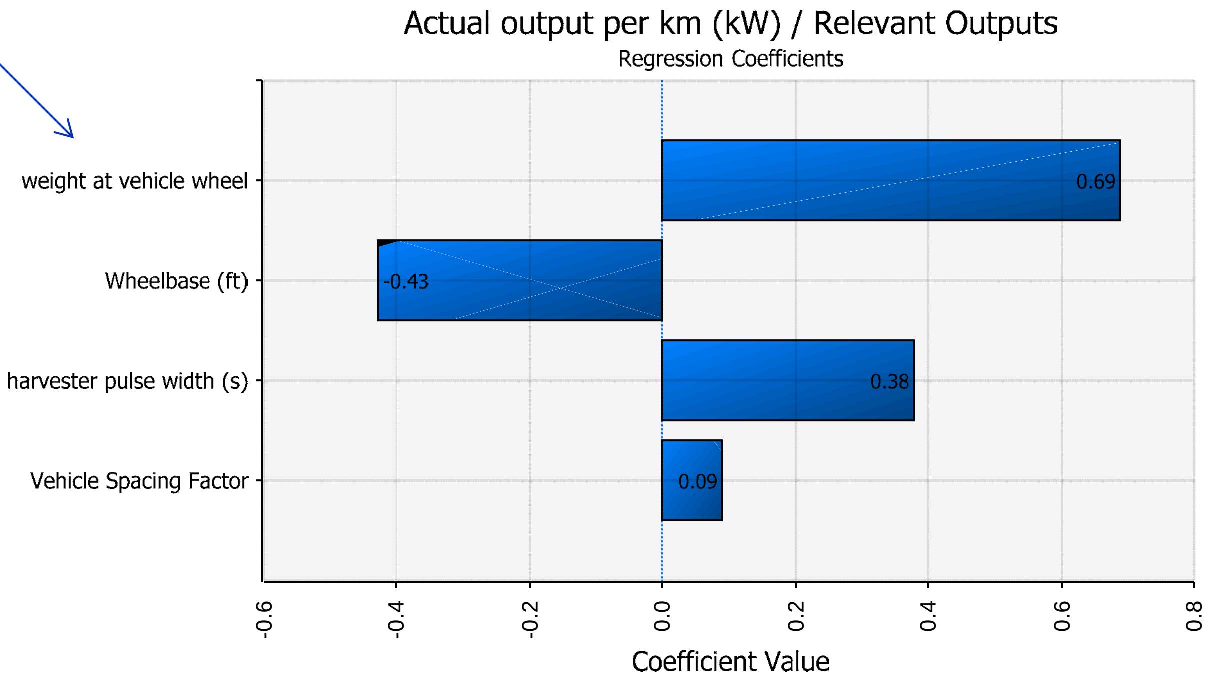
kW/km is a location specific metric

How to test this?

Test with measured loads and generate power vs. load plot



We need this for commercial systems.



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Homing in on 300 W/ft^2

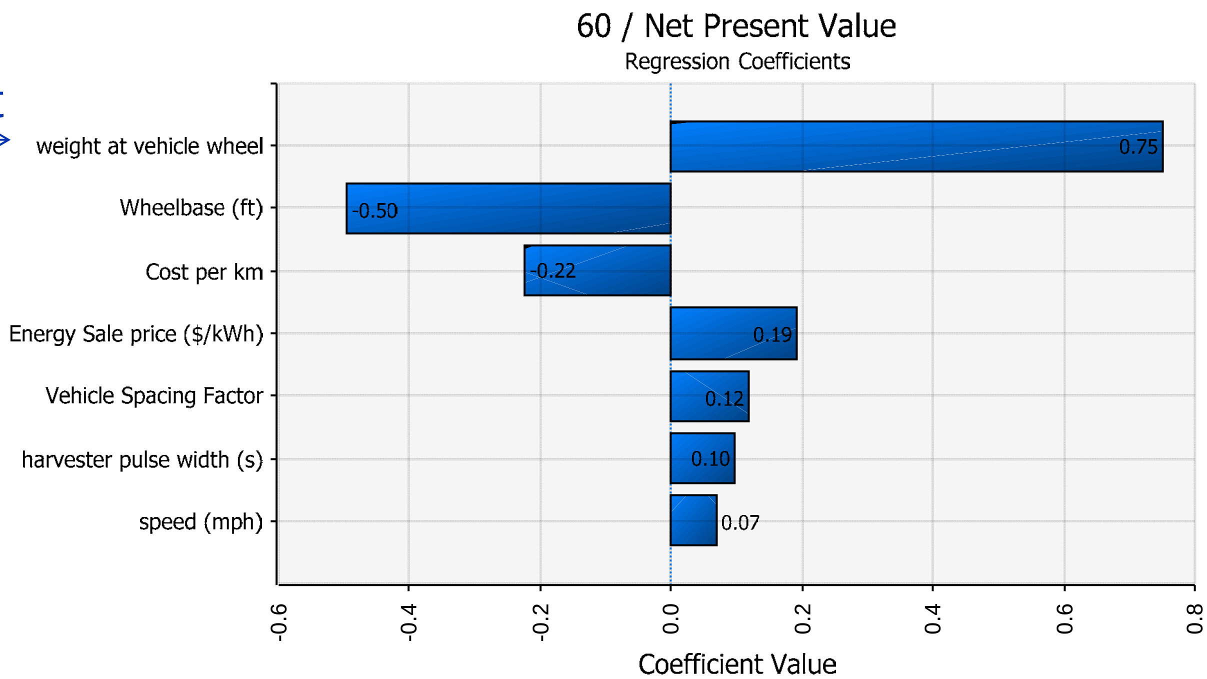
Power Output per Harvester (W)	50th Percentile NPV at 5 Years	LCOE ($/kWh)	Capital Cost of System ($/kW)	Nameplate Power Density (W/ft^2)	Actual kW/km
79	-$451,000	$0.19	$17,100	179	38
132	-$313,900	$0.11	$10,200	298	64
265	$30,190	$0.06	$5,100	596	128

- Power density >300 W/ft^2 (in this case a module output >150W)
- A 10-20 year lifetime
- Capital costs <$10,000/kW
- Actual kW/km > 100

Estimation of Net Present Value – Regression Coefficients

Like other renewable energy systems, the technology is best optimized when placed in an area where the environment maximizes its use.

~ power per unit



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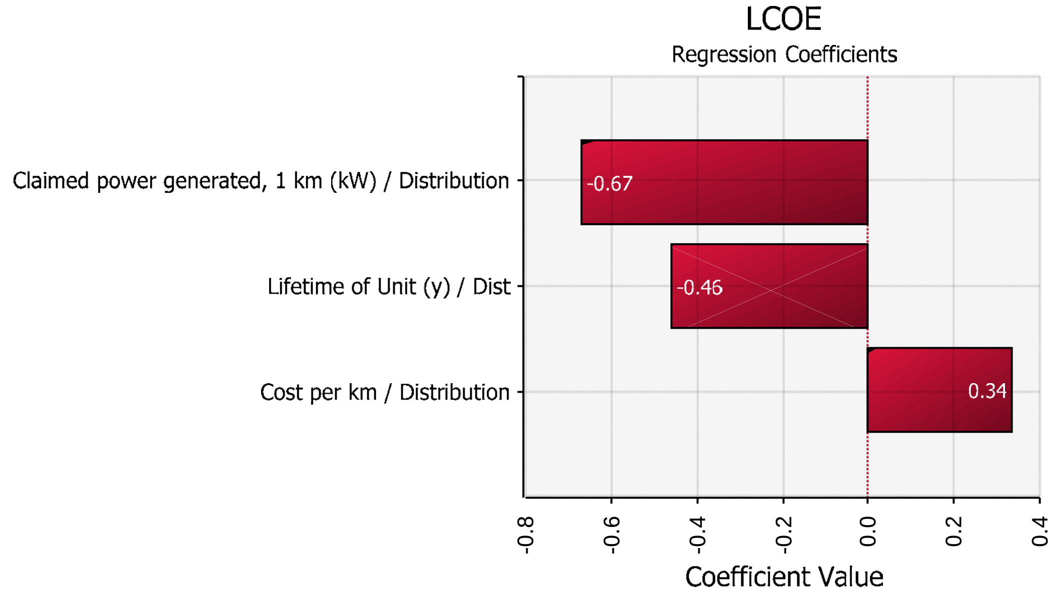
Estimation of LCOE for Compression Based Energy Harvesters using Available Vendor Data

Case	Minimum LCOE (/kWh)	Maximum LCOE (/kWh)	Mean LCOE (/kWh)	Standard Deviation, LCOE (/kWh)
Case 1: Maximum 5 Year Lifetime	$0.027	$1.15	$0.18	$0.14
Case 2: Maximum 10 Year Lifetime	$0.014	$0.41	$0.08	$0.05
Case 3: Maximum 30 Year Lifetime	$0.004	$0.20	$0.03	$0.02

Uncertainty embodies traffic parameters and module output



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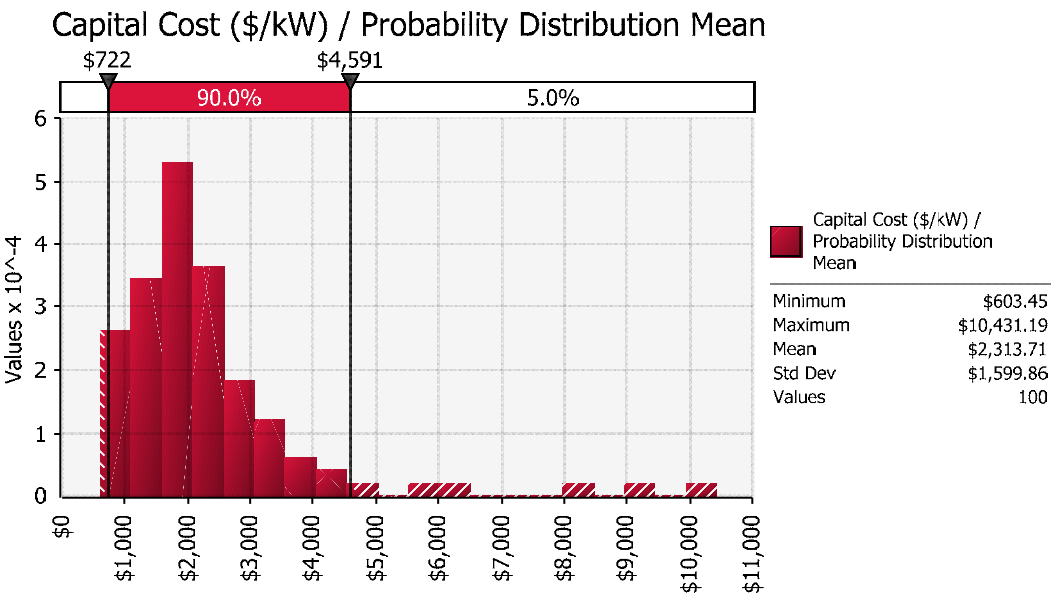
Assessing Capital cost



90% of values lie between $700-$4600

Not a “gaussian” type distribution – great uncertainty on the long tail.

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Possible Mutual Exclusivity?

- Harvester spacing: 8”
- Harvester pulse width: 0.1s
- Lifetime: 10-20 years
- Length of installation: 1 km
- Cost of Installation: $650,000
- Traffic speed: 45 mph
- Vehicles per hour: 600

Fixed Paramater	**LCOE = $0.11/kWh**	**kW/km = 100-200**	
	Traffic Model	Traffic Model	Innowattech
Power per unit (W)	132	265	Not given
Capacity factor	0.05	0.05	Not given
Capital cost	$10,200/ kW	$5,100/ kW	Mean $2,300/ kW, see **Error! Reference source not found.** – max is $10,400/ kW
Nameplate Power Density (W/ ft^2)	298	596	Not given
Actual capacity factor adjusted output (kW/ km)	64	**128**	100-200
Nameplate system power (kW/ km)	1,303	2,607	Not given
LCOE ($/ kWh)	**$0.11/kWh**	$0.06/ kWh	Calculated in previous section

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Vibration Based Energy Harvester LCOE Estimate based on Vendor Claims

Case	Minimum LCOE (/kWh)	Maximum LCOE (/kWh)	Mean LCOE (/kWh)	Standard Deviation, LCOE (/kWh)
Case 1: Maximum 5 Year Lifetime	0.05	0.22	0.10	0.03
Case 2: Maximum 10 Year Lifetime	0.03	0.04	0.03	0.004
Case 3: Maximum 30 Year Lifetime	0.01	0.01	0.01	0

Not much spread or uncertainty because only 1 reference was found.

Possible areas of Mutual Exclusivity

- Harvester spacing: 24”
- Harvester pulse width: varied between 0.2-1.0s
- Lifetime: 10-20 years
- Length of installation: 1 km
- Cost of Installation: $27,200,000
- Traffic speed: 65 mph
- Vehicles per hour: 600

Difficult to match $0.06/kWh **and** 13.6 MW **and** 41% capacity factor **and** $2,000/kW

Fixed Paramater	LCOE = $0.06-0.08/kWh	kW/km = 13,600	Capacity Factor = 42%	Capital Cost = $2,000/kW	
Reference	Traffic Model	Traffic Model	Traffic Model	Traffic Model	Genziko
Power per unit (W)	3,973	12,714	2,649	13,243	Not given
Capacity factor	0.32	0.32	**41%**[1]	0.32	32-42%
Capital cost	$6,521	$2,038	$7,744	**$2,065/kW**	$2,000/ kW
Nameplate Power Density (W/ ft^2)	993	3,178	662	3,311	Not given
Actual capacity factor adjusted output (kW/ km)	4,201	**13,444**	3,538	13,267	13.6 MW/ km
Nameplate system power (kW/ km)	13,035	41,712	8,690	43,450	Not given
LCOE ($/ kWh)	**$0.07/kWh**	$0.02/ kWh	$0.09/ kWh	$0.02/ kWh	$0.06-$0.08/ kWh

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Idealized System using the Traffic Model

This exercise illustrates mutual exclusivity between LCOE and capital cost.

All of this depends on uncertainty about the module power output.

If this were known, it would make these analyses much more transparent.

	Fixed: \$0.11/kWh	**Fixed: \$4,000/kW**
LCOE	~~\$0.11/ kWh~~	\$0.04/ kWh
Capital Cost (\$/ kW)	\$9,615/ kW	\$4,172/ kW
Capacity Factor	0.09	0.13
Vehicle Flow Rate (vehicles/ hr)	611	611
Vehicle Weight Distribution (N/ wheel)	26,486	26,486
Power Per Unit (W)	143	185
Unit Spacing (in)	8	8
Nameplate Power Density (W/ ft^2)	322	417
Nameplate Power System Rating (kW/ km)	1,408	1,825
Actual System Output (kW/ km)	107	149
Units per km	9,843	9,843
Power Pulse Length (s)	0.1-0.2	0.1-0.5
Average vehicle wheelbase (ft)	11.24	11.24
Vehicle Speed (mph)	60-70	60-70
Cost per km (\$/ km)	\$600,000 - \$1,500,000	\$600,000 - \$1,500,000

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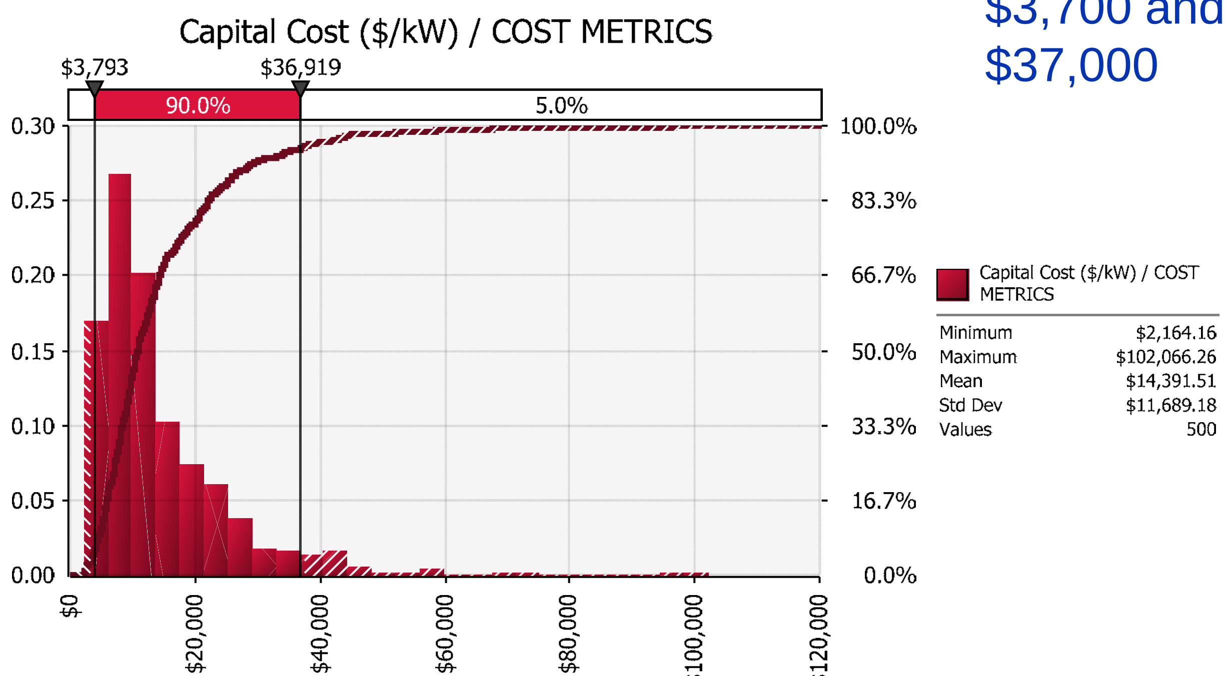
CAPEX

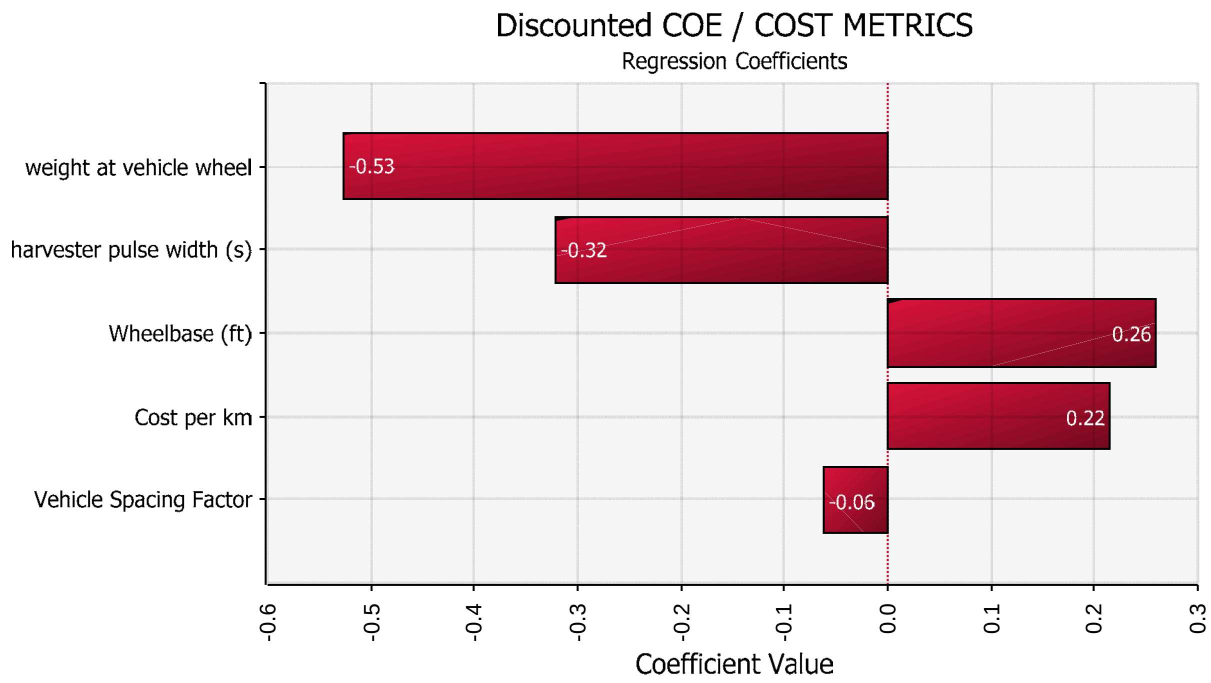
Mean = $14,391/kW

90% of CAPEX lie between $3,700 and $37,000

Wide uncertainty = lack of knowledge about certain parameters



Regression for LCOE and CAPEX identical



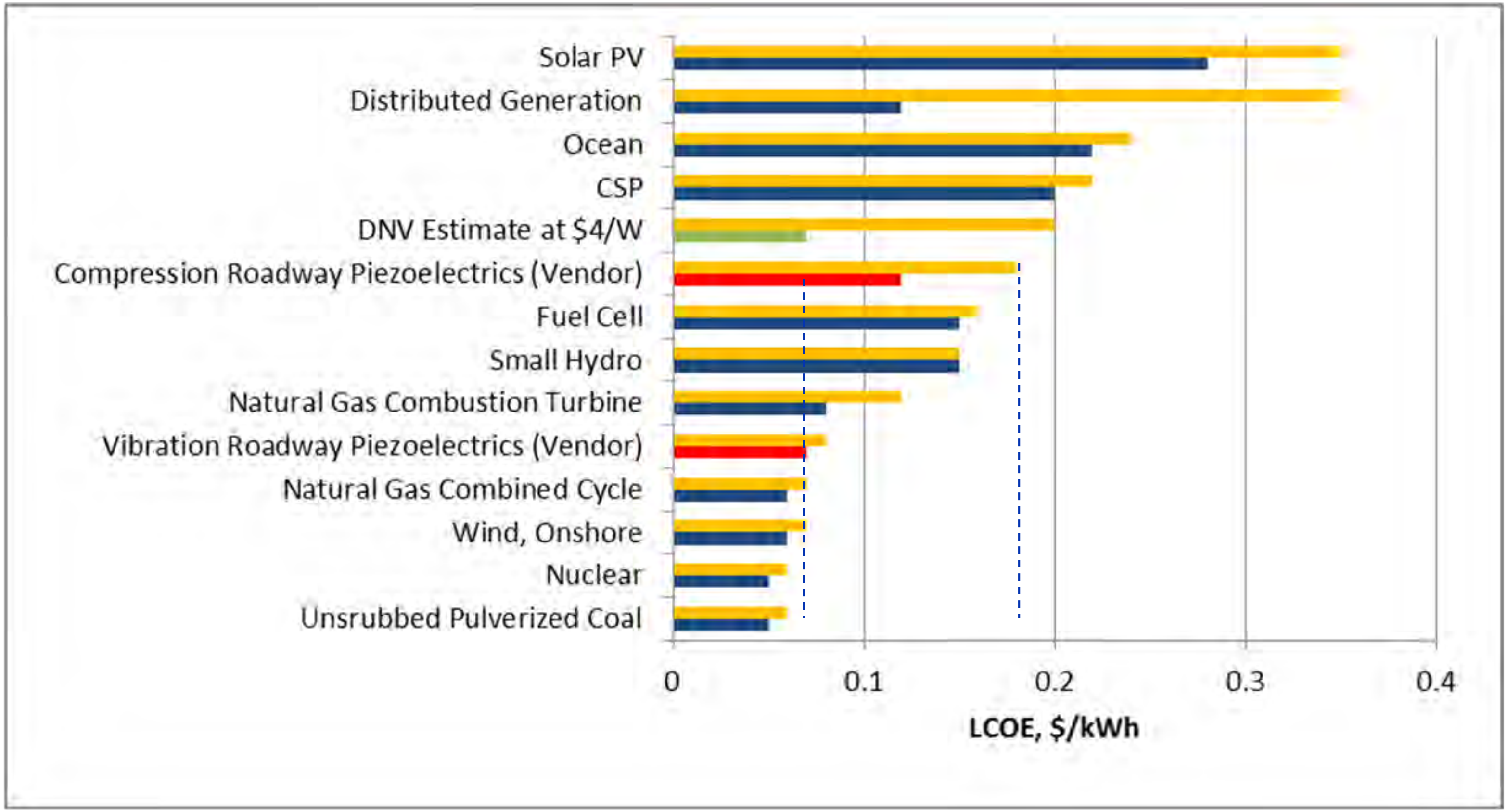
Ways to narrow down LCOE and CAPEX estimate:

1. Build the system for specific traffic characteristics
2. Increase power pulse width

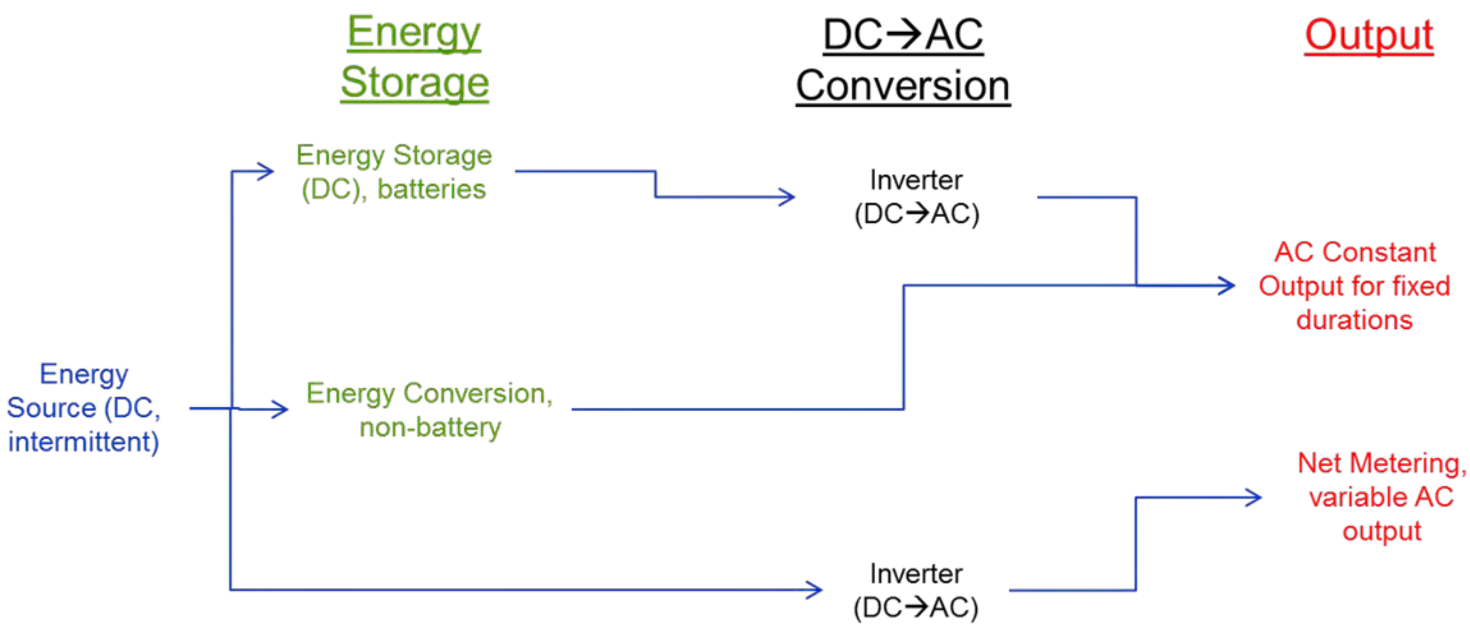
Things to consider in practical evaluation of real world system

- What is the maximum power output in controlled conditions?
- What do these conditions imply about real world conditions?
- What vehicles shall be targeted for the installation?
- Optimize the system for these specific characteristics.

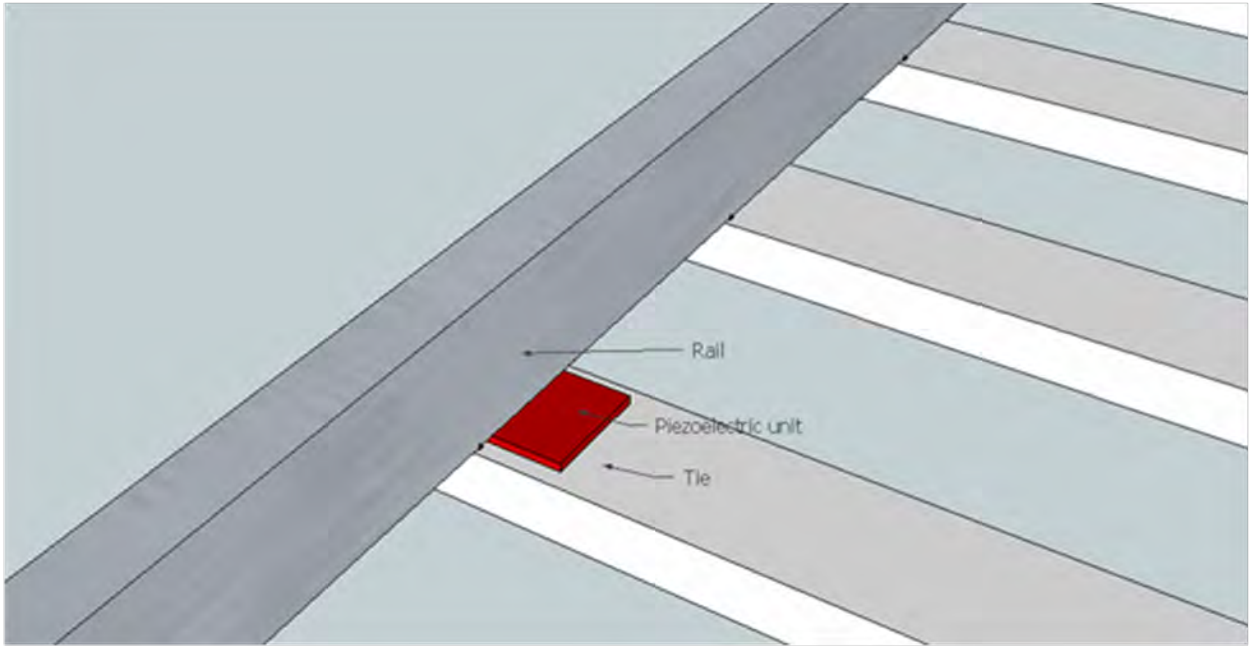
Piezoelectric LCOE



Energy Storage or Net Metering?



What about railways?



Simplified installation

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Recommendations for Evaluation

Stage-Gate

Test module power output first.
Model actual output in roadway.
Recalculate LCOE and CAPEX.

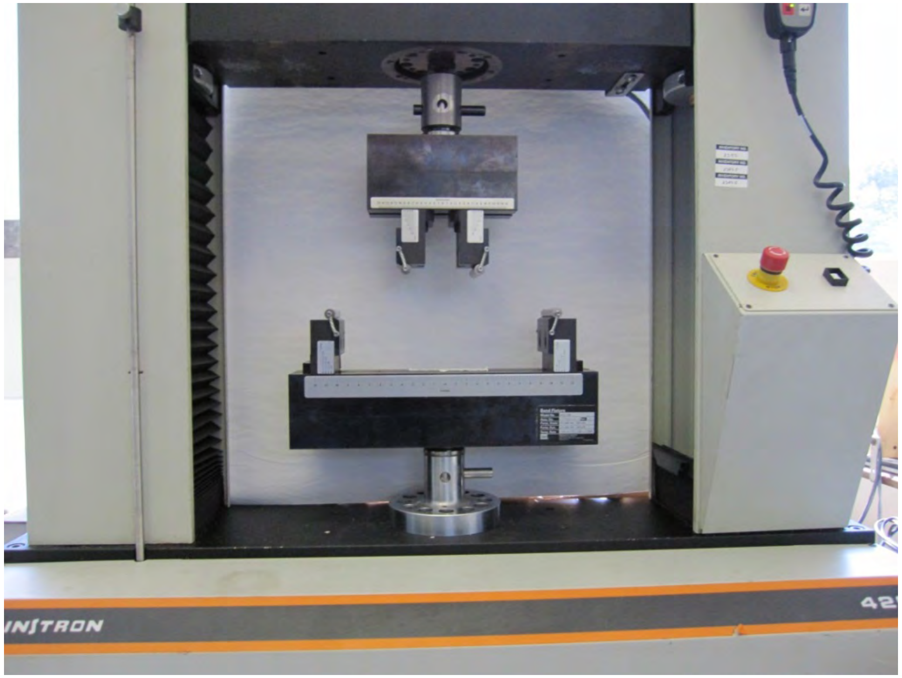
If promising, proceed to accelerated tests.

If promising, proceed to demo.

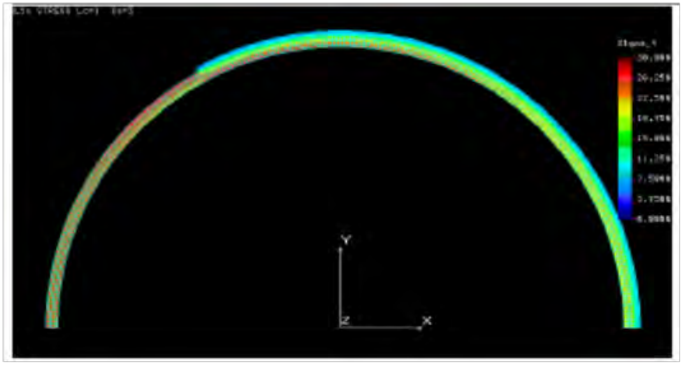
Phase Description	Expected Result/Outcome	Pass/Fail Criteria
Validation of Power Output per module	Tentaively we calculate a power output of 300 W/ ft^2 is required to make the system viable. If power output is promising or if any vendor claims are verified, proceed to Phase II. Determine top performer, select pathway for implementation (road or rail)	Using calculation approaches in this report, verify that power output matches the needed levels for payback to reach the targeted power densities or power per km metrics. If it does not, it shall not proceed to Phase II.
Accelerated Tests	Identify decay mechanisms and durability issues. Reduced list of products from Phase I will be tested. If durability and failure modes are acceptable, proceed to Phase III.	For products that have made it to Phase II, they shall show a cycle life equivalent to critical lifetime, such as 10-20 years. Should account for weathering and other abuse factors.
Field Demonstration	For durable products that have shown acceptable power output, a field demonstration in an appropriate environment should be chosen.	Actual use data should verify the needed power output and durability requirements.

Lab Scale Tests

Confirmation of module output is a priority.

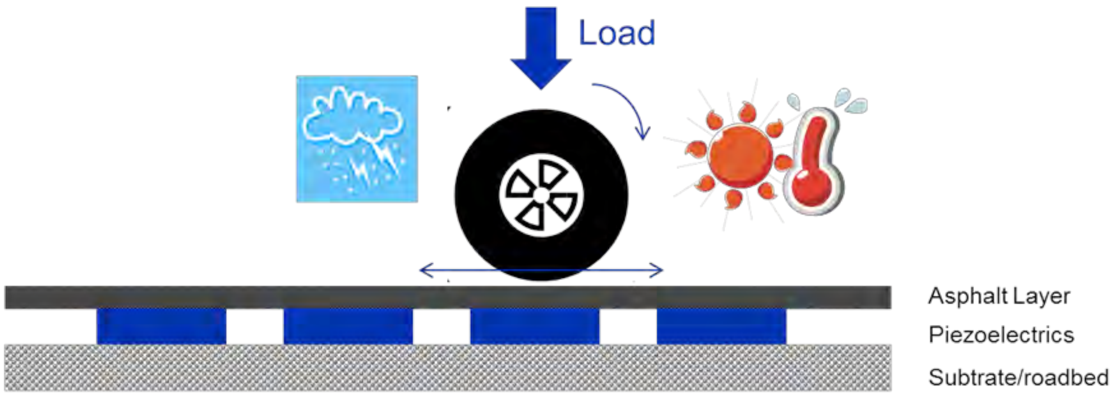


FEA Models



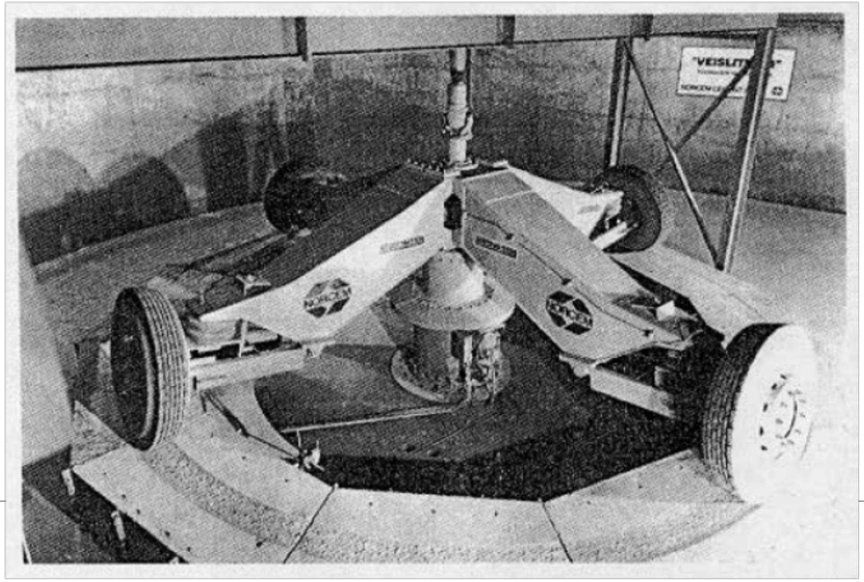
Test load vs. power output

Possible Accelerated Testing Methods

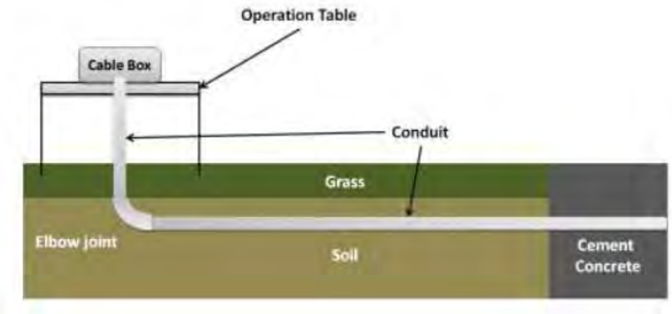


Purpose:

Accelerated wear and weathering, durability of materials and total system.



Possible Demo Configurations



Source: Virginia Tech

In the event of a demonstration, installation in the roadway may look similar to what was done by Virginia Tech.

Safeguarding life, property and the environment

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